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A PERSPECTIVE OF SYNTHETIC APERTURE RADAR FOR REMOTE SENSING.(U)

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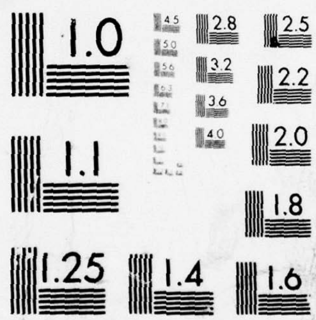

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NRL Memorandum Report 3783

A Perspective of Synthetic Aperture Radar for Remote Sensing

M. I. SKOLNIK

Radar Division

May 1978

NAVAL RESEARCH LABORATORY
Washington, D.C.

18 SBIE 19 AD-E000 186

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

9 **REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

NRL Memorandum Rep[redacted]t 3783

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

14 NRL-MR-3783

4. TITLE (and Subtitle)

6 A PERSPECTIVE OF SYNTHETIC APERTURE RADAR FOR REMOTE SENSING

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

10 Merrill [redacted] I./Skolnik

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

Naval Research Laboratory
Washington, D. C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

N/A

11. CONTROLLING OFFICE NAME AND ADDRESS

12. REPORT DATE

11 May [redacted]78

13. NUMBER OF PAGES

~~18~~ 12 19p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Radar
Synthetic aperture radar
SAR
Remote sensing of the environment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Because of its unique capability for providing good resolution in the cross-range, as well as the range dimension, synthetic aperture radar has proven to be of considerable interest for remote-sensing applications over both the land and the sea. In this tutorial report the characteristics and capabilities of synthetic aperture radar are discussed so as to identify those features particularly unique to SAR. Brief comparison is made between SAR and optical images. SAR is an example of a radar that provides more information about a target than simply its location. It is the spatial

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S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

78 07 10 066

20. Abstract (Continued)

resolution and imaging capability of SAR that has made its application of interest, especially from spaceborne platforms. However, for maximum utility to remote sensing, it has been proposed that other information be extracted from SAR data, such as the cross section and the variation of cross section with frequency and polarization. Several of the special problem areas that might possibly limit the utility of SAR are mentioned, such as complexity, swath and resolution, image interpretation, need for calibration, EMC, as well as the handling of the large amounts of data generated from remote sensing applications.

CONTENTS

A PERSPECTIVE OF SYNTHETIC APERTURE RADAR FOR REMOTE SENSING*

1. Introduction

The synthetic aperture radar (SAR) has the unique capability of providing good resolution in the along-track, or cross-range, dimension as well as in the range dimension. This ability to provide an image-like high-resolution display has caused the SAR to be of considerable interest for remote sensing of the sea and land. This paper reviews some of the background of synthetic aperture radar as it relates to remote sensing, and discusses some of the issues involved in its application. The intention is to provide an introduction to this Technology Conference.* The point of view is that of a radar systems engineer interested in the application of SAR technology, and is not that of a specialist involved in the daily pursuit of improved SAR technology. Thus the comments presented here can be considered as the impressions of an interested observer viewing a dynamic and important radar field that has attracted much interest for its potential applications.

The SAR offers promise for remote sensing because of its unique characteristics that have already been demonstrated, as well as its yet undemonstrated potential for extracting further information about an object, to supplement that already provided by the spatial resolution.

In this report a brief description will be given of synthetic aperture radar concept and its special characteristics that make it of interest for remote sensing. This will be followed by a listing of some of the major applications of SAR and its proposed use in remote sensing. The emphasis is on application from satellites. Several of the special problems involved in the use of SAR will then be discussed. The tone of the report is part tutorial and part "editorial," in that it is both a technical review and a means for expressing the writer's opinions and impressions of SAR as a radar tool for remote sensing.

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*This report is an extended version of the keynote paper presented at the Synthetic Aperture Radar Technology Conference, March 8-10, 1978, Las Cruces, N.M., sponsored by the NASA Johnson Space Flight Center and the New Mexico State University Physical Science Laboratory.

Note: Manuscript submitted April 28, 1978.

The SAR concept is indeed a significant radar accomplishment. One version of where it fits within the major accomplishments in radar during the last 40 years might be as follows:

1930's - Early development of the basic concept of radar.
1940's - Microwave radar development.
1950's - Practical utilization of coherent (doppler) radar, as in *synthetic aperture radar*, MTI and cw.
1960's - Digital processing, and HF OTH radar.
1970's - Extraction of information, other than "blob information" from radar signals.

Thus SAR ranks high in the inventory of radar accomplishments. The development of digital processing in the late 60's has enhanced the practical utility of SAR. Also, the SAR has contributed significantly in the 70's to the increased extraction of information from the radar signal.

2. The SAR Concept

The SAR may be considered from one of two viewpoints depending on whether the frame of reference is at the target or at the radar. These are: 1) as a sequentially synthesized array antenna of large effective aperture or 2) as the use of the doppler-frequency domain to spatially resolve different parts of objects having different doppler-frequency shifts because of different relative velocities with respect to the radar. Both points of view have been successfully utilized in the analysis and development of SAR. It is not uncommon in SAR analysis to switch from one model to another, depending on which is the more convenient for describing some particular property of the system. Although SAR is usually thought of in terms of a synthesized antenna, it was the doppler viewpoint that first guided the original experimenters in this area. When viewed as the use of the doppler domain to achieve the equivalent of angle resolution, it can be seen that SAR is related to the *scatterometer* that uses a broad fan beam with doppler filters to achieve resolution in elevation. The use of doppler by the radar astronomer to image the planets (also called range-doppler imaging or inverse synthetic aperture) is also based on the same physical principle as SAR.

The real-aperture antenna of a synthetic aperture radar is generally directed perpendicular to the flight path of the vehicle. In this configuration it is a *sidelooking radar* that produces a strip-map image of the terrain. The real-aperture antenna may also be directed forward or aft of the perpendicular. This is called the *squint mode* and also produces a strip map. Synthetic aperture processing can also be employed with a circular-scanning antenna to provide enhanced resolution on a PPI, except in a sector centered about the forward or aft direction of the vehicle trajectory. This is called the *doppler beam-sharpening mode*. A positionable antenna can be made to dwell on a particular area to

achieve a longer observation time, and thus provide better resolution than a fixed aperture. This is called the *spotlight* mode. It is also possible to obtain multiple looks of a particular scene with a fixed real-aperture antenna by trading resolution for a number of independent observations. The noncoherent superposition of these multiple looks of lower resolution produces a less speckled image than does a single observation of higher resolution. SAR has also been employed to obtain stereoscopic images of terrain.

The development of SAR began in the early 50's and took almost a decade to reach significant levels of application. The development of SAR and its original application were sponsored by the military, primarily for all-weather battlefield surveillance and as a reconnaissance sensor. Although it has seen important application for the military, it has been more of a complement to other military sensors rather than as a supplement.

Compared to other radars, SAR has the unique capability of obtaining resolution in the cross-range, or along-track, dimension comparable to the resolution obtained in range. With other radars the resolution in cross-range is determined by the antenna beamwidth and is usually considerably greater than the range resolution. The SAR is able to image a scene and obtain information about the scene by the spatial relationships and contrasts provided by the high resolution. The imaging and mapping qualities of SAR allow terrain features and man-made objects to be recognized, and their spatial relationships identified and utilized. In this regard its output is somewhat like an optical photograph, but with some important differences. The search for additional information that can be extracted from the received signal in both SAR and conventional radar continues. In the area of remote sensing it is especially important to extract other information about the objects being viewed. The resolution provided by SAR allows the isolation of the various objects of interest from those that might contaminate the measurement.

A cursory examination of a SAR image and an optical or IR image of the same scene, especially from long range, might give the impression that the active radar and the passive optical and IR images are similar and thus competitive. Actually there are significant differences between these sensors. These may be described as:

a) The almost 10^5 difference in wavelength between radar and optical (visual) frequencies means that the two sensors will respond to different size scatterers, as well as require significantly different equipment technology. Scattering occurs from those scale-sizes that are comparable to the incident wavelength. Thus SAR will detect scattering from those scatterers with dimensions of the order of centimeters. Optical imaging sensors are responsive to scatterers of the order of microns. Thus "radar eyes" are different than "optical eyes." The information provided is different, and different criteria are required in

the interpretation of the images obtained by SAR than the usual techniques of photographic interpretation.

b) Another major difference between the two classes of sensors is that the radar responds to its own illumination. Visual imaging sensors (and some IR sensors) require ambient illumination, as from the sun, and are thus limited to daylight and by the location of the sun relative to the sensor. IR imaging sensors also depend on differences in the temperature and emissivity of the various objects of the scene. Areas near the poles with visibility and sunlight conditions poorly suited for photography can be readily imaged by SAR since it does not depend on sun angle. The usual viewing angles of radar can result in shadows produced by high relief such as hills and mountains which can be used to obtain information regarding the three-dimensional character of the terrain. These shadows are generally not evident in optical photographs.

c) Since optical and IR passive sensors view objects with incoherent ambient illumination or incoherent radiation from the objects themselves, the result is an image to which the eye is accustomed. The image produced by a coherent SAR, however, is of a speckled nature, not unlike that seen by an object with laser light. The speckled nature of the scene can make its interpretation difficult, and can cause confusion to an interpretor not familiar with this effect. To minimize the effect of speckle, SAR radars sometimes superimpose multiple independent images of the same scene taken with different frequencies and viewing angles.

d) The resolution of a "focused" SAR is independent of range, whereas that of passive imaging systems is worse with increasing distance. This makes SAR of interest from spacecraft where the ranges are large.

e) Radar has the advantage of being able to operate any time of the day or night and under weather conditions that make IR or optical sensors inoperative. This advantage, in the writer's view, is not necessarily a *major* reason for using radar in remote sensing. Most remote sensors do not require "timely" data. If it is raining on one pass it might not be on the next pass. If an optical sensor capable of operating only in the day passes over an important area at night, consideration can be given to using a second satellite to insure at least one pass in daylight during a specified time. Radar can be all-weather when used for imaging the spatial relations of the elements of a scene. But if other specific information is needed, such as for soil moisture measurement or crop identification, the effect of rain might degrade the ability of SAR to provide reliable data. Radar has a decided advantage, however, in areas of the world with a continuous weather problem, as in those cloud-covered regions located at $\pm 15^{\circ}$ about the equator.

3. Applications of SAR, Especially for Remote Sensing

Although SAR does a different job than any other radar, and has unique capabilities, it has not enjoyed the wide application experienced by the more classical radar. The "bread and butter" application that would sustain a major segment of the electronics manufacturing industry has yet to appear. Nevertheless, its continual development is pursued and there continues to be significant interest in its application.

In short-range remote sensing from aircraft, the classical noncoherent high-resolution radar that obtains cross-range resolution with a physically large antenna with narrow beamwidth has proven competitive to coherent SAR. When its resolution is adequate, the lower cost, absence of sophisticated processing, and an image relatively free from speckle make it the preferred approach in many applications. However, at long range, as from a satellite, the resolution of a conventional antenna is inadequate for most purposes and synthetic aperture must be used to achieve resolution. The increased integration time (or effective aperture length) of the SAR with increased range helps compensate in part for the lower echo signals at the longer ranges.

The specific applications of SAR from spaceborne platforms will not be discussed here since that is the subject of another paper in this Conference ("Applications of Space-Borne SAR Data," by Fawwas T. Ulaby.) The general application areas that are contemplated or proposed may be described as follows:

a) Measurement of sea state and sea spectrum

This is the objective of the NASA SEASAT-A. The resolution of the SEASAT imaging radar is coarser than might be desired, but it is a first attempt to demonstrate the utility of SAR for remote sensing from space. Other radars and other sensors can obtain a measure of sea state, but SAR is the only all-weather remote sensor (other than HF OTH radar) with the potential for obtaining the two-dimensional sea spectrum. This SAR capability was first demonstrated by the Soviets using conventional imaging radar from aircraft.

b) Geological and mineral exploration

This is the prime objective of the NASA SIR-A (Shuttle Imaging Radar) experiment. Conventional noncoherent imaging radars on aircraft have been widely accepted as a tool for petroleum exploration. Imaging radar has also been used for mapping and mineral exploration of inaccessible areas by several South American countries, presumably with success.

c) Agricultural measurements

The chief measurements desired in this area are soil moisture

and crop classification. This is the objective of SIR-B. These are difficult measurements to make with radar. There has been much preliminary work in this area, but it is not as far advanced as the other two application areas mentioned above since it is a more difficult task. Determination of soil moisture, as now proposed, requires an accurate, absolute measurement of the radar cross-section as well as *a priori* information about the nature and roughness of the scattering objects. It has been proposed that crop identification can be performed using multiple frequency and/or multiple polarization observations. The degree of success of these two measurements of soil moisture and crop identification has yet to be determined.

d) Other remote sensing applications

SAR also has been demonstrated or suggested to be used for mapping of watersheds and flooded regions, ice mapping and identification, oil-spill detection, measurements of snow water-content, observation of precipitation, urban land-use monitoring, among others. It has also been used, of course, for military purposes.

Of the above, SEASAT is planned for launch in 1978, SIR-A has been approved as a NASA program and is planned for July 1979 launch. The above applications of SAR are not without competition by other sensors. Almost all of these measurements might be obtained by other means, even though such a competitor as optical and IR imaging are not all-weather, and microwave radiometry, another serious competitor, is not capable of the same resolution as is SAR.

4. Attributes of SAR

The features of the SAR that make it of interest for remote sensing include the following:

a) Good resolution in the along-track, or cross-range, coordinate as well as the range coordinate. This provides a map-like presentation which permits the identification of objects by their spatial relationships, size and shape.

b) Resolution cell size independent of range.

c) Ability to produce images from satellite ranges.

d) All weather.

e) Potential ability to extract information regarding roughness, symmetry, and dielectric properties of scattering media within the resolution cell.

f) Additional information possible with multiple frequency, dual polarization, and spatial diversity observations.

g) Real-time processing and display either on board the sensor platform or by remote transmission of radar output.

h) Information can be obtained from scattering objects not possible with optical or IR sensors, because of the use of microwaves. (A good example is that of geological prospecting where information on lineaments is found with microwaves but not found with optical photographs.)

i) The technology of SAR is well developed and there has been considerable experience with its application as an imaging device so that its current capabilities and current limitations are understood.

j) The SAR technology is applicable over a wide range of frequencies, from VHF to millimeter wavelengths.

5. Issues and Concerns in the Potential Application of SAR

As with any device, SAR cannot do everything that may be desired of it. In this section, some of the areas of concern in its use are briefly mentioned. (The listing below is in no special order.)

a) Complexity and Resolution

The SAR is more complex and expensive than ordinary radar, as might be expected. However, there have been continual improvements made in the hardware, especially in the signal processing.

The complexity of an SAR is related to the resolution desired. It seems conceivable that better resolution than is now utilized can be obtained, especially at the higher microwave frequencies. However, it has been found in some applications that the ultimate in resolution is not always needed or even desirable, even if expense and complexity are not deciding factors. That is, the optimum resolution for any particular application is not necessarily the smallest resolution cell that can be obtained. It might even occur that too much resolution is harmful to the type of information desired. Traditionally, in mapping radars the along-track resolution and the range resolution are made equal, or nearly so, in order to present conventional-looking images. Perhaps this practice ought to be reexamined critically for remote-sensing applications. It is far easier to obtain high resolution in the range dimension than in the along-track dimension. If asymmetrical resolution can be tolerated, a simpler radar will result.

The highest resolution obtainable with an SAR is with a focused system that corrects for the curvature of the wave front experienced when imaging objects in the Fresnel region of the synthetic antenna. An *unfocused* SAR is not capable of as great a resolution as a focused system. Also the cross-range, or along-track, resolution of an unfocused SAR is not independent of range, but varies as the square

root of the range. In spite of such limitations, the lesser complexity of the unfocused SAR might make it a contender for those applications for which the ultimate in resolution is not required.

b) Magnitude of Data Available from SAR

The high resolution of the SAR results in a high data rate and a large amount of information. The handling of large quantities of data as can be obtained with a SAR can saturate and overwhelm some users interested in the radar information. Careful planning is required in what information is to be obtained, and in its efficient analysis. Some users believe that the increased data rate from an SAR will result in more information than they can digest. This might indeed be true, but it should not be a reason for restricting the resolution to a lesser value than might be desired. As mentioned above, there is generally an optimum resolution for any particular application, determined by what is to be imaged and the information desired. If the total amount of data that can be handled is limited for some reason, then the choice between a large quantity of images of poorer resolution, or a lesser quantity of images of optimum resolution, must be carefully considered. The proper handling of large amounts of data is an area requiring more attention.

c) Swath

There is a limit to the coverage, or swath width, obtainable with a SAR. The swath depends on the resolution. This is due to the ambiguities in both angle and range when a sampled (pulsed) radar system is used. A high prf is necessary to achieve high resolution images without ambiguities causing overlap and superposition of images. On the other hand, a low prf is necessary in order to image a large swath in the range coordinate without the range ambiguities causing image overlap. Thus there is a trade between swath width S_w and resolution δ_a, which is given by

$$\frac{S_w}{\delta_a} = \frac{c}{4v \cos\phi}$$

where v is the velocity of the vehicle, c the velocity of propagation and ϕ is the grazing angle. This equation was derived assuming optical processing, a flat earth and a vertical beam shaped to illuminate only the swath S_w. It would have to be modified when the curvature of the earth cannot be neglected. For a spacecraft with a velocity of 7500 m/s, with cos $\phi \approx 1$, a swath of approximately 100 km is theoretically possible with a resolution of 10 m.

In addition to the fundamental limit on swath and resolution set

by the pulsed (sampled) nature of the radar signal, there will also be practical limits set by the complexity of the available signal-processing technology and the limited ability of a user to handle large amounts of information.

Thus one of the severe limitations of a SAR for space application is the limited swath width, which might be no more than several hundred kilometers, or less. Although this might seem to be adequate for many applications and is comparable to that achieved by optical and IR images on Landsat, it does not take full advantage of the coverage that can be viewed from a satellite, which can be in the vicinity of 1000 to 3000 km for low and medium orbit heights. The limited swath means that many satellites must be used to obtain worldwide daily coverage, or that only limited parts of the earth will be covered if a single satellite is used. This is another reason for using only the resolution needed for the particular application, and no more. (The paper by J. Eckerman and J. P. Claassen in this Conference, entitled "A System Concept for Wide Swath Constant Incident Angle Coverage," proposes a multiple beam radar configuration for increasing the swath.)

Space systems that view the earth's surface should have a large swath coverage in order to obtain timely information over a large part of the earth in an economical manner. Unfortunately large swaths with SAR are obtained at the expense of poor resolution. If SAR is to provide full benefit in space applications, its swath should be larger than has generally been considered. At present, there do not appear to be any simple solutions available.

d) Coverage and Revisit Time

A swath coverage of about one hundred kilometers typical of the experimental SARs proposed for remote sensing applications from space results in a long revisit time of the same area on the surface of the earth. This might be 10 to 15 days in some cases. Several of the proposed applications of SAR require more timely revisits. This means a larger and more complicated satellite radar with a large swath is required, or there must be more satellites. The need for proper coverage and revisit time might be of little concern for the exploratory phases of remote sensing on which NASA is now embarked, but it is an issue which cannot be neglected when operational systems are considered where cost-benefit is a criterion for the spending of funds. This is a fundamental issue that must be faced by the technologists.

e) Image Interpretation

An image produced by a SAR is similar to an optical photograph. However, there are significant differences between the two, so that someone trained to interpret optical photographs might not extract the proper information from a SAR image. Even with the same

resolution there can be significant differences between the two because of the large difference in wavelengths of the two sensors and the speckle in the SAR image. Each sensor responds to those scattering objects with dimensions comparable to the wavelength. With SAR there will likely be greater variation in echo strength as a function of viewing angle than with optical imaging. Thus different passes over the same area with SAR can result in differences in the images. The coherent nature of microwave radiation results in a speckled image due to constructive and destructive interference. This does not occur with optical or IR imaging which depends on incoherent radiation. Speckle can be reduced in the SAR by observing the same scene with different frequencies and/or from different viewing aspects, and noncoherently superimposing the resultant images.

f) Signal and Data Processing

Past improvements in digital processing circuitry have resulted in improved real-time processing either on- or off-board the satellite. Developments in digital processing are continuing and further improvements for SAR can be expected.

g) Equipment

Unfortunately there do not now seem to be any significant developments in spaceborne radar transmitters that would lead to significantly smaller, more efficient packages for space application. If radar in space is to be a permanent tool for operational remote sensing, basic work in transmitters is indicated. The present conference includes a number of papers on antenna design, indicating an awareness of the importance of the antenna to a spaceborne SAR. Cost of equipment is an important consideration. The cost is not only in dollars, but in the space and weight that must be accommodated in a spacecraft. Radar is not small. If radar can perform a desired function for remote sensing, then one should not be afraid of large systems and should strive to obtain what is needed, rather than what would be tolerated.

h) Information Extraction

Work has been underway to obtain information about the objects within a scene based on a measurement of the absolute value of the cross-section within a resolution cell, as well as by measuring cross section as a function of frequency, polarization, or both. The measurement of the absolute value of cross section per unit area, as has been suggested as needed for certain remote sensing applications, is a difficult measurement to make to the desired accuracy. If useful measurements are to be derived from other than the spatial relationships, some other measurement is needed. A method for extracting information, that seems as yet untapped, is the employment of pattern recognition or two-dimensional matched filtering comparison to classify one type of terrain from another on the basis of the spatial

pattern of the return. For example, in a one square mile of terrain there are approximately 3800 resolvable cells when the radar has a resolution of 30 m, and about 34,000 cells with 10 m resolution. It would seem that there are distinctive elements that might be uncovered by proper processing.

i) Frequency and Space Diversity

Some proposed SARs for Earth Resources Survey are to view the same scene with more than one frequency and at more than one aspect. The purpose of these multiple images is to superimpose them so as to smooth out the speckle that appears with coherent radar and obtain a less gainy image more like that seen with incoherent light. The potential benefit from frequency diversity and spatial diversity will make it likely that such SARs will be considered further, possibly along with polarization diversity. Such diversity likely would improve the ability of pattern recognition to recognize one type of scene from another.

j) Statistics of Land and Sea Echo

Several of the papers in this conference (Korwar and Lipes, Pierce and Korwar) assume the statistics of the echo within a pixel, or resolution cell, are described by the Rayleigh probability density function. This may be true of receiver noise and low-resolution radar, but it is not true of land and sea backscatter. It is well known that with high resolution, the probability density functions for both sea and land echo have higher "tails" than that given by Rayleigh statistics. The log-normal pdf is sometimes used as a model for the extreme case of non-Rayleigh statistics, but the Weibull pdf, which lies between the Rayleigh and the log-normal, seems better able to model most examples of non-Rayleigh clutter. Different constants (such as mean-to-median ratio, standard deviation, or Weibull coefficient) apply for different terrain and sea conditions and for different radar resolutions. It is not obvious what effect the non-Rayleigh pdf has on those analyses in which Rayleigh statistics are assumed, but it is a consideration that needs to be kept in mind. It is suggested that a Weibull or some other suitable non-Rayleigh pdf be used in analyses of SAR remote sensing.

The fact that different forms of terrain and sea conditions result in different Weibull coefficients might be used as a means for identifying one form of terrain from another. Measuring the parameters of the pdf of a patch of terrain might be one method for obtaining classification, but there might well be others.

k) Calibration, Accuracy and Precision

The measurement of soil moisture as proposed for remote sensing from space with synthetic aperture radar appears to require the absolute measurement of the radar cross section per unit area σ^o.

Absolute measurements require good calibration and good stability of the radar. From past experience with attempts to measure the absolute value of radar cross section, it is unlikely that the measurement of σ^o can be consistently made to an accuracy better than $\pm$ 3 dB, or at best $\pm$ 2 dB. (The precision of measurement might be better.) There is no fundamental reason why a more accurate measurement of σ^o cannot be made, but this seems to be a practical limit that has been hard to make better. A $\pm$ 3 dB accuracy is apparently not satisfactory for soil moisture measurement or for accurate measurement of wind with a scatterometer. Several of the papers in this conference treat the problem of radar calibration. It is an important problem that is one of the major limitations in several remote sensing applications.

Even if it were possible to calibrate the radar to any accuracy desired, there is still the problem of statistical variation of the measurement itself which can limit the ability to obtain *average* values with small variance. The σ^o of the terrain might not be uniform, and the speckle associated with coherent radar observations might require long-term averages to obtain meaningful measurements. It is not unusual for two passes over the same terrain to give as much as 10 dB difference in measured σ^o.

At the present time SAR is best used where absolute measurements of σ^o are not required. The chief attribute of SAR is to provide the resolution needed for imaging and for recognizing effects by the shape, position, and relative intensity of the scattering objects.

ℓ) Millimeter Wavelengths (frequencies greater than 40 GHz).

There has always been interest in the application of millimeter wavelengths for radar, above K_a band. One of the reasons millimeter wavelengths have not had application is the large attenuation through the earth's atmosphere, especially at low grazing angles. If higher grazing angles can be utilized, millimeter waves might be of interest since their scattering properties might be different than at lower frequencies. (There is no evidence at present that would suggest that millimeter waves will provide significant new information not attainable with lower frequencies, but the possibility that it does should not be overlooked.)

m) Synchronous Orbits

Synchronous satellites have the advantage of being able to observe continuously a large portion of the earth's surface. A synthetic aperture radar cannot be precisely synchronous since relative motion is required between the radar and the scene being viewed, hence the term near-synchronous SAR. (One approach is described in the paper by Tomiasu.) A satellite in near-synchronous orbit requires larger real-antenna apertures and large powers in order to achieve the

necessary signal-to-noise ratios from such large distances. It is not likely that near-synchronous orbit SAR will be seriously considered (that is, large funds spent) before closer-orbit satellites or aircraft SAR have proven the value of the measurements to be made.

n) Electromagnetic Compatibility (EMC)

The potential interference between a satellite radar and ground equipments can be quite serious. Not only is the mutual interference problem aggravated by the large ground area within the line-of-sight of an SAR in a satellite, but an SAR for remote sensing applications will be of high power and with a broad signal bandwidth. In some applications there is proposed multiple frequency operation, which further complicates the EMC problem.

If a conflict results between a spaceborne radar and ground electromagnetic services, the application with greater economic impact (or greater military or national need) will likely be the one given priority for the use of the electromagnetic spectrum. As the SAR proves its worth for remote sensing, the potential problems of EMC and spectral occupancy must be kept in mind. If SAR does create a serious interference problem to other services, its use will have to be justified. It is thus important to pay special attention to the needs of the potential users of SAR so as to maximize its economic potential.

o) Sustaining Applications and Competitors

There have been a whole host of applications proposed for the spaceborne SAR. There are many potential users of the information derived from a SAR that have expressed interest in seeing data from such a sensor. However, there seem to be few, if any, potential users of SAR who are serious enough to pay the large costs involved for a useful operational system, even assuming developmental costs are paid by someone else. There is insufficient knowledge available at present to allow a prudent investor to make that kind of decision. More information is needed regarding what such systems will eventually be able to do. If a sustaining "bread and butter" application is not found, interest in SAR for space application likely will wane. More effort is required in ferreting out suitable applications for SAR. Mere "interest" by some user is not sufficient. Evidence is required to prove that SAR has the potential for performing an important function not capable of being fulfilled by some other sensor, or that it can perform a needed function more effectively or more cheaply than by any other method.

6. Discussion

Synthetic Aperture Radar certainly offers potential for unique capabilities for remote sensing from space. Current SAR technology can

provide more information than will be obtained with SEASAT-A or SIR-A. There exists an available hardware base from which to draw, as well as new technology developments as evidenced from this meeting and the continued developments under NASA sponsorship. Theoretical analyses, ground experiments, aircraft experiments, as well as the interests of potential users, all support the need for further efforts. However, the current base of knowledge is still inadequate to march confidently into the future with a definitive plan that will lead to operational spaceborne SAR systems performing some needed function in an economical affordable manner. Conferences such as this one are important if that goal is to be reached. There are certainly unresolved problems with SAR for remote sensing. If there were none, then there would be no need for R&D. Problems are a natural consequence of pioneering efforts.

SAR must provide something other than is provided by IR and optical images, or by microwave radiometers. Also, it must be shown that operational satellite-borne SAR offers a competitive cost-benefit advantage over aircraft-mounted SAR. With its use of microwave wavelengths, its own controlled source of illumination, ability to use many octaves of the spectrum, control of polarization, its potential wide swath and adequate resolution, SAR offers some significant differences over other sensors. These differences should be exploited for remote sensing applications.

One thing this paper has not done, since it is not within the capability of the writer to do so, is to describe what SAR needs that it does not now have, that would allow it to be a major sensor for remote sensing from space. Before it will be widely used, it must be verified that SAR from space can achieve an important remote sensing capability better and/or cheaper than any other means, and that this capability is something of economical or societal value.

GENERAL REFERENCES ON SYNTHETIC APERTURE RADAR

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